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INTERNATIONAL PUBLIC POLICY INSTITUTE
CENTRE FOR ENERGY POLICY

Increased energy efficiency in Germany: International spillover and rebound effects

Simon Koesler, Centre for European Economic Research
Kim Swales, Department of Economics, University of Strathclyde
Karen Turner, Centre for Energy Policy, University of Strathclyde

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OCCASIONAL PAPER

International spillover and rebound effects from increased energy efficiency in Germany

Simon Koesler, Kim Swales and Karen Turner

Abstract

The pollution / energy leakage literature raises the concern that policies implemented in one country, such as a carbon tax or tight energy restrictions, might simply result in the reallocation of energy use to other countries. This paper addresses these concerns in the context of policies to increase energy efficiency, rather than direct action to reduce energy use. Using a global Computable General Equilibrium (CGE) simulation model, we extend the analyses of 'economy-wide' rebounds from the national focus of previous studies to incorporate international spillover effects from trade in goods and services. Our focus is to investigate whether these effects have the potential to increase or reduce the overall (global) rebound of local energy efficiency improvements. In the case we consider, increased energy efficiency in German production generates changes in comparative advantage that produce negative leakage effects, thereby actually rendering global rebound less than national rebound.

JEL classifications:
D58; Q41; Q43; F18; Q56

Keywords:
Energy supply; energy demand; rebound effects; energy efficiency; general equilibrium; trade spillover; energy and pollution leakage

1. Introduction

Existing research identifies the importance of trade effects on the nature and magnitude of economy-wide rebound where domestic energy efficiency improvements have occurred (Hanley et al., 2009; Van den Bergh, 2011). Whilst Wei (2010) presents a theoretical analysis of 'global rebound' and there are a number of applied studies, including Barker et al. (2009), the potential spillover effects from energy efficiency improvements in one nation on energy use in other nations have generally been neglected (Madlener and Alcott, 2009; Sorrell, 2009; Turner, 2013; Van den Bergh, 2011).

This is an important knowledge gap, particularly given the global nature of energy-related climate change and the existence of supra-national policy targets, such as the EU 20-20-20 framework. Potential interaction across geographic boundaries implies that energy efficiency target setting and policy implementation decisions in different countries should be considered as interdependent. This is of particular interest given the pollution leakage literature (e.g. Babiker, 2005; Böhringer and Löschel, 2006; Löschel and Otto, 2009; Elliot et al., 2010), which produces examples where environmental policies enacted in some countries simply result in shifting the pollution generation or energy use to other countries. This pollution leakage typically occurs through international changes in production and trade patterns. Here we relate the leakage issue to policies that directly improve energy efficiency and consider the potential for both positive and negative leakage effects of energy efficiency improvements in one country on energy use (and related emissions) in others (Baylis *et al.*, 2014; Bento *et al.*, 2012). Specifically we investigate how the concept and treatment of economy-wide or 'macro-level' rebound can be extended to take into account these wider impacts.

Rebound occurs when improvements in energy efficiency stimulate an increase in the direct and/or derived demand for energy in production and final consumption. It is triggered by the fact that an increase in energy efficiency increases the effective energy services gained from each physical unit of energy used. This reduces the price of energy, measured in efficiency (or energy service) units (Berkhout *et al.*, 2000; Birol and Keppler, 2000; Brookes 1990, 2000; Greening *et al.*, 2000; Herring, 1999; Jevons, 1865; Saunders, 1992, 2000a,b; Schipper and Grubb, 2000; Van den Bergh, 2011). Recent reviews of the literature are given in Dimitropoulos (2007), Sorrell (2007) and Turner (2013) whilst Maxwell *et al.*, (2011) and Ryan and Campbell (2012) provide policy-focussed reviews.

The economic impacts of increased energy efficiency in general, and rebound pressure in particular, spread to the wider economy through a series of price and income effects. So-called 'economy-wide' rebound studies have generally been conducted in the context of improved efficiency in industrial energy use within individual national or regional economies. The most common approach is to use multi-sector Computable General Equilibrium, CGE, models. These are reviewed in Sorrell (2007) and more recent studies include Anson and Turner (2009) and Turner and Hanley (2011). The aim of this paper is to augment this literature by extending the spatial focus of the wider rebound effects using a multi-region CGE world model, developed along the lines of the basic version of the WIOD CGE framework (Koesler and Pothen, 2013). [1] In Section 2, we consider the types of channel through which an efficiency improvement in *productive* energy use (i.e. within industries/production sectors rather than the household final

[1] This paper separately identifies all EU countries but treats the rest of the World (ROW) as a single aggregate entity. However, in the reported results the European Union is separated into Germany and the rest of the EU (REU) so that when we refer to regions, we mean aggregations of national states.

consumption sector) in one nation can spill-over to impact energy use in direct and indirect trade partners.[2] In Section 3, we derive the analytical expressions required to extend the rebound calculation to incorporate endogenous changes in energy use at extended spatial levels. In Section 4, we provide an overview of the world CGE framework that we use. This adopts the type of specification commonly used to consider issues of pollution leakage resulting from implementing environmental policies (e.g. Babiker, 2005; Böhringer and Löschel, 2006; Löschel and Otto, 2009; Elliot *et al*., 2010). In Section 5, we outline the simulation strategy and in Section 6 we present results from two sets of simulations. These are both for a 10% increase in energy efficiency in production in the German economy. In one case this applies only to the "Manufacturing" sector. In the other, it applies in all production sectors. Results are reported for the change in key economic variables in Germany, the rest of the EU (REU) and the rest of the world (ROW). Section 7 calculates a number of alternative rebound values for these efficiency improvements. Section 8 draws conclusions and recommendations for future research.

2. Extending the boundaries of the economy-wide rebound effect

2.1 Home Economy Effects

2.1.1. Energy efficiency improvements in a single sector

Where the energy efficiency improvement applies to only one (target) sector, the home-economy impacts that affect rebound operate through the following channels. First, there is substitution towards energy, measured in efficiency units, in production in the target sector. This operates through the fall in the price of energy used in production in that sector, when that energy is measured in efficiency units. This means that the proportionate fall in energy use, now measured in natural units, per unit of output in that sector is less than the efficiency improvement. The second channel is the increased competitiveness of the target sector. This is driven by the reduced costs associated with the reduced intermediate input use. Both the substitution and competitiveness effects increase the rebound value. A third channel is the reduction in energy use through the energy sector supply chain. Energy production is energy intensive. A reduction in demand for energy in the target sector will further reduce the demand for energy in the production of energy itself. This third channel reduces the rebound value.

Additional home-economy impacts are driven by the changes in the general use of energy as an intermediate input to supply production and also to directly meet changes in consumption demand. As argued already, we expect the output of the target sector to rise and output in the

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[2] Lecca et al. (2014) investigate the economy-wide impacts of increased efficiency in household energy use. These differ from the impacts generated by the improvements in productive energy use considered here.

energy sector to fall (as long as there is no 'backfire', i.e. rebound greater than 100%). However, the actual composition of output across other sectors will depend on the sectoral reallocation of the fixed factors, capital and labour, driven by the adjustments to factor prices. These changes in factor prices, together with the change in the technology in the target sector, are reflected in all commodity prices which are determined simultaneously in equilibrium. These prices drive the relative competitiveness of the sectors and, together with the composition and price sensitiveness of final demands, will act to further impact economy-wide rebound.

2.1.2. An energy efficiency gain in all sectors

Where the energy efficiency gain applies to all sectors, there will be the same home economy substitution effect leading to increased energy use in production, when measured in efficiency units. This now operates in all sectors and remains a major channel for rebound. However, the ultimate size of the competitiveness effect for individual sectors will be affected by their energy intensity. It is clearly the case that with fixed, fully-employed, factors of production output cannot rise in all sectors simultaneously. The price of factors in general will increase (although there will normally also be distributional effects). Therefore, some sectors will actually lose competitiveness, even though their energy efficiency has risen. However we expect that the more energy intensive sectors will experience the bigger cost reductions and, therefore, ultimately be those that are more competitive after the efficiency increase. In this respect, it is important to note that energy itself is a highly energy intensive sector, so that it is likely to be one of the sectors whose competitiveness increases.

2.2 Foreign Economy Effects

In all cases the economies of countries that do not directly experience an improvement in energy efficiency are affected through three channels. Two of these relate to changes in trade-related demand (the changes in exports and import substitution). The third is the accompanying changes in intermediate and consumption demand.

The changes in trade-related demand are determined through competitiveness and composition of demand channels. The relative competitiveness effects are primarily governed by price changes in the home economy. If the price falls in a particular home sector, we expect that the competitiveness of the corresponding sector in other countries will fall with an accompanying negative impact on output. Similarly, if the composition of home-country import demand changes for non-price reasons, this affects the export demand in foreign countries. Such a demand change would include shifts in energy demand directly affected by the increased energy efficiency.

However, it is important to note that the changes in foreign energy exports or import substitution do not directly affect energy use in foreign countries. If more energy is exported this means that the energy is to be used elsewhere. However, the third, supply-chain, channel is important in this respect. This is the change in intermediate demands that accompanies the changes in trade-related demands.

There are additionally other general equilibrium impacts but these are likely to be less important. There are possible changes in the energy intensity of production that would accompany changes in relative energy prices. Similarly, if consumption demand increases through favourable changes in the terms of trade, this will affect energy demand. However, we expect the primary impact to come through changes in intermediate demand driven by changes in the size and composition of export demand.

3. Quantifying rebound in a multi-regional setting

Here we build on the economy-wide rebound specifications derived in Lecca *et al.* (2014) to consider the general equilibrium rebound effects of a proportionate improvement in the efficiency with which energy is used in a single production sector. Own-sector rebound in the targeted sector *i*, is identified as R_i, and is reported in percentage terms. It implicitly incorporates general equilibrium feedback effects on sector *i's* energy use, in addition to direct and indirect rebound effects. It is defined as:

$$R_i = \left[1 + \frac{\dot{E}_i}{\gamma}\right] 100, \tag{1}$$

where $\dot{E}_i$ is the change in energy use in sector *i* after all agents have adjusted their behaviour in consequence of the technical energy efficiency improvement, $\gamma > 0$. Both the energy efficiency improvement, γ, and the change in energy use, $\dot{E}_i$, are given in percentage terms. To reiterate, this is not direct rebound; rather it is the rebound calculated incorporating the change in energy use in sector *i* with all general equilibrium effects of the efficiency improvement taken into account.

The first step in identifying the own-country economy-wide rebound effect is to consider the impact of the proportionate energy efficiency improvement in the treated sector *i* on total energy use in the aggregate production side of the economy (all *i*=1,…,N sectors), E_p.

The own-country total production rebound formulation, R_p, is given as:

$$R_p = \left[1 + \frac{\dot{E}_p}{\alpha\gamma}\right] 100, \tag{2}$$

where α is the initial (base/reference year) share of sector *i* energy use in total energy use in production (across all *i*=1,…,N sectors) in the domestic economy. The term $\dot{E}_p/\alpha\gamma$ can be expressed as:

$$\frac{\dot{E}_p}{\alpha\gamma} = \frac{\Delta E_p}{\gamma E_i} = \frac{\Delta E_i + \Delta E_p^{-i}}{\gamma E_i} = \frac{\dot{E}_\imath}{\gamma} + \frac{\Delta E_p^{-i}}{\gamma E_i}, \tag{3}$$

where Δ represents absolute change and the -i superscript indicates all production excluding sector *i*. Substituting equation (3) into equation (2) and using equation (1) gives:

$$R_p = R_i + \left[\frac{\Delta E_p^{-i}}{\gamma E_i}\right] 100. \tag{4}$$

This shows that the total (own-country) rebound in productive energy use will be greater than the own-sector rebound if there is a net increase in aggregate energy use across all other domestic production sectors. On the other hand, if there is a net decrease in total energy use across these sectors, then total rebound in production will be lower than own-sector rebound.

Using a similar procedure, detailed in Appendix A, we can show that the full economy-wide rebound effect in the domestic economy, R_d, can be expressed as:

$$R_d = R_p + \left[\frac{\Delta E_c}{\gamma E_i}\right] 100. \tag{5}$$

where the *c* subscript indicates 'consumption' (households). Equation (5) indicates that the total economy-wide rebound in the home country, *d*, will be larger (smaller) than rebound in the aggregate production sector if there is a net increase (decrease) in energy use in household final consumption.

In this paper we are particularly interested in the international energy-use spill-over effects. Therefore, we define a global rebound effect, R_g, relating to the total impact on energy use in all countries resulting from increased efficiency in the use of energy in sector *i* within the home economy, *d.* Again, adopting a similar approach, outlined in Appendix A, this can be expressed as:

$$R_g = R_d + \left[\frac{\Delta E_g^{-d}}{\gamma E_i}\right]100 \tag{6}$$

where E_g^{-d} represents global energy use outwith the domestic economy receiving the efficiency shock. Again, expression (6) shows that the total economy-wide global rebound will be greater than the own-country rebound if there is a net increase in external aggregate energy use following the efficiency improvement within country *d*. If there is a net decrease then total global rebound will be lower than own-country rebound. Note that it is possible to identify more than one region within the external global economy and disaggregate the changes in global non-domestic energy use accordingly. We do this below in our case study of increased efficiency in German industrial energy use by separately identifying the change in energy use in the rest of the EU-27 and the rest of the world.

4. The global CGE modelling framework

To evaluate the economy-wide rebound and provide a first analysis of the full international spill-over effects that accompany an increase in domestic energy efficiency, we make use of a static, multi-region, multi-sector CGE world model which has been developed along the lines of the Basic WIOD CGE (Koesler and Pothen, 2013). In the present analysis the model feature 28 separate regions. These comprise all the individual EU27 member states and Rest of the World (ROW). However, for ease of exposition, in presenting the simulation results we aggregate the outcomes for all EU member states apart from Germany, so that we report figures for Germany (GER), the Rest of the EU (REU) and the Rest of the World (ROW).

The model disaggregates production to eight sectors/commodities. Two are energy supply sectors/commodities: “Electricity and Gas” and “Coke, Refined Petroleum and Nuclear Fuel”. The other six (non-energy supply) sectors/commodities are “Primary Goods”, “Food, Drink and Tobacco”, “Manufacturing”, “Construction”, “Transport” and “Services”. The mapping of these aggregate sectors to the original WIOD sectors is given in Table B.1 in Appendix B.

The production of each commodity is characterised by a KLEM production structure shown in Figure 1, which features a CES function at every level. Capital, $K_{(r)}$, and labour, $L_{(r)}$, enter the production function on the lowest level in the generation of value added. On the second level the value added composite is combined with the energy intermediate composite $A_{(eg,r)}$. This energy composite is a (fixed coefficients) Leontief aggregation comprising the commodities “Electricity and Gas” and “Coke, Refined Petroleum and Nuclear Fuel”. On the top level the energy-value-added composite is combined with a non-energy material aggregate $A_{(neg,r)}$ to create the sector gross output, $Y_{(i,r)}$.[3]. The intermediate composite is also a Leontief aggregation of all six non-energy commodities identified above. Sectoral output can be used for intermediate use, final domestic consumption or exported. Commodities are made up of composites of the domestic production and imports, using the Armington (1969) assumption of incomplete substitution.

Each region has one aggregated representative agent who supplies a fixed amount of capital and labour. Both factors are immobile between regions but completely mobile across sectors within each region. All factors are fully employed, which determines the relevant wage and capital rental payments. This implies a Marshallian long-run interpretation of the simulation results, in that in each equilibrium all factor use is fully adjusted to the ruling factor and commodity prices.

The consumption decision of the representative agent embraces all the household and governmental (private and public) final demand in a region. The representative agent maximizes her utility by purchasing bundles of consumption goods subject to a budget constraint. The budget is determined by factor and tax income along with interregional borrowing or saving. The utility of representative agents $U_{(r)}$ is given as a Leontief composite of energy $A_{(eg,r)}$ and a non-energy commodities $A_{(neg,r)}$. The structure of the utility functions is shown in Figure 2.[4]

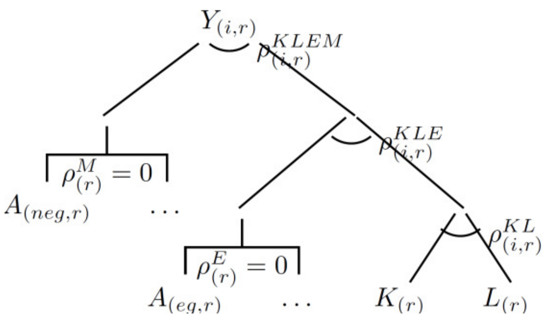

Figure 1: Structure of commodity production

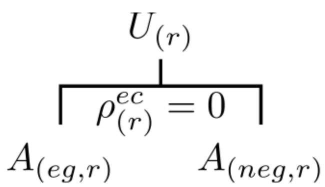

Figure 2: Structure of utility function

[3] There are other ways of structuring the nested KLEM production function and there are also other possible functional forms (Lecca et al., 2011). Alternative CES structures and functional forms will be investigated in future work.
[4] Modelling consumption on the basis of a Leontief function is restrictive, although it has recently been endorsed by Herrendorf et al. (2013). We investigate the sensitivity of the rebound value to variations in the elasticity of substitution in consumption in Appendix B, Tables B.2 and B.3.

Regarding the basic economic structure, the model builds on data from the World Input-Output Database (WIOD) (Timmer et al., 2012; Dietzenbacher et al. 2013) and is calibrated to the year 2009.[5] The structure of the Armington trade aggregation is shown in Figure 3, with the corresponding Armington elasticities taken from GTAP7 (Badri and Walmsley, 2008; Hertel *et al.*, 2007; Hertel *et al.*, 2008). For substitution elasticities determining the flexibility of production with regard to inputs, we turn to estimates from Koesler and Schymura (forthcoming).[6] Savings and borrowing are not directly reported in WIOD but they result from the imbalance of final demand and factor endowments or other sources of revenue (taxes, emission allowances, etc.). Overall macroeconomic balance is achieved by changes in interregional savings/borrowing, whilst the overall savings and borrowing of final demand agents are held constant. Prices are expressed against the numeraire which is taken to be the consumer price index (CPI) for the rest of the World.

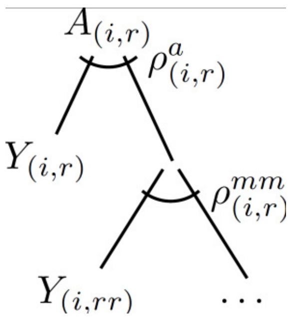

Figure 3: Structure of Armington aggregate

5. Simulation strategy

We wish to simulate the impact of the adoption of energy-saving technological change in production. As is standard in rebound studies, we assume that this technological change is supplied as a public good. This implies that the efficiency improvement is assumed to be costless in two respects. First, resources are not required to create the knowledge on which the efficiency improvement is based. Second, firms can implement the efficiency changes without using additional resources. We make these assumptions because the study of rebound focusses on the difference between actual and expected energy saving from the introduction of improved energy efficiency. It is the reduced cost of energy in efficiency units which drives the

[5] The WIOD database is available at http://www.wiod.org. We use data downloaded on the 17th of April 2013.

[6] Koesler and Schymura (forthcoming) fail to provide substitution elasticities between capital and labour for the “Electricity and Gas” sector or for the substitution elasticity between value-added and energy in the production of “Coke, Refined Petroleum and Nuclear Fuel”. For these setors we assume an elasticity equal to the corresponding elasticity in the “Manufacturing” (0.234) and the “Chemical and Chemical Products” sectors (0.717) respectively.

rebound effects. The simulations attain maximum transparency if the efficiency improvements are assumed to be costless. It is important to distinguish the rebound effect associated with pure efficiency improvements from the wider impact of policies, such as carbon pricing or cap and trade schemes, which achieve a reduction in the use of energy only through the use of previously more costly other inputs.[7]

We therefore follow the common procedure adopted in CGE studies of economy-wide rebound by examining the effects of an exogenous step increase in the efficiency of energy used as an intermediate input. We consider two scenarios. In both, we apply a 10% technical improvement in German energy efficiency in production.[8] In the first simulation this applies solely to the "Manufacturing" sector. In the second scenario, the energy efficiency stimulus is experienced by all eight German production sectors. In each case, the new post-shock equilibrium is then compared to the original equilibrium (without the efficiency changes) and the appropriate rebound values are calculated. This therefore represents a comparative static analysis in which all changes can be attributed to the efficiency shock.[9]

The energy efficiency shock is applied to the second nest of the treated sectors' production functions (see Figure 2) which take the form:

$$CES_{KLE(i,r)}^{KLEM} = \left(\eta_{KL(i,r)}^{KLE} \left(CES_{KL(i,r)}^{KLE} \right)^{\rho_{(i,r)}^{KLE}} + \gamma_{(i,r)}^{Energy} \eta_{E(i,r)}^{KLE} \left(\min_{eg} \left(\frac{A_{(eg,r)}}{\eta_{(eg,r)}^{E}} \right) \right)^{\rho_{(i,r)}^{KLE}} \right)^{\frac{1}{\rho_{(i,r)}^{KLE}}}, \quad (7)$$

where, η are input shares, ρ are substitution parameters and γ^{Energy} indicates the level of energy efficiency which is normalised to be one in the initial equilibriium. The proportionate change in demand for intermediate energy use would apply equally between domestic and imported electricity as long as relative electricity prices remained the same. In the first scenario the efficiency parameter, $\gamma_{\text{i,GER}}^{\text{Energy}}$, in equation (7), increases from its initial value of 1 to 1.1 in the German "Manufacturing" sector only. In the second scenario, the parameter is increased across all German production sectors.

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[7] However, the issue of the costs associated with efficiency improvements is one that is often raised in discussions of simulating efficiency changes. This is addressed in more depth in Appendix C.

[8] On average the energy efficiency of the German industry has increased by about 1.6% per annum (BMWi, 2013). In the process of our analysis, we also considered efficiency improvements of 5%, 20% and 30%. But as the magnitude of the shock only affects the scale of the different effects and does not change the underlying basic effects. Here we report findings which would correspond to just over 5 years worth of technical improvement, mapping to an energy efficiency improvement of 10%.

[9] In future work we aim to consider more sophisticated ways of simulating efficiency improvements, for example by modelling a link with R&D activity, as proposed by Fisher-Vanden and Ho,(2010).

It is useful to give an indication of the size of shock that is to be given to the international economy through these efficiency changes. Table 1 shows the energy used in German "Manufacturing" and in German production as a whole as a share of total energy use in German production, the German economy as a whole, the combined EU and the world economy.[10] The data show that the energy use in "Manufacturing" makes up 28.58% of the total energy used in German production. Energy used in German production is 57.99% of total German domestic energy use, and 10.81% and 2.95% of all EU and World energy use. It is clear that we would expect energy efficiency improvements in German "Manufacturing" and in German production as a whole to have impacts which would spread outwith the German national border.

Table 1
The energy used in German "Manufacturing" and German production expressed as a percentage of total energy used in German production, and the German, EU and World economies.

	German production (α)	German economy (β)	EU economy (ϕ)	World economy (χ)
German "Manufacturing"	28.58	16.57	3.09	0.84
German Production	100.00	57.99	10.81	2.95

Source: Authors' calculations based on WIOD,
(Timmer et al., 2012; Dietzenbacher *et al.*, 2013)

6. Impacts of a 10% increase in energy efficiency in the German "Manufacturing" sector and in all German production

6.1 Simulation 1: 10% increase in energy efficiency in German "Manufacturing"

In this sub-section we consider the effects of an energy efficiency improvement, targeted on the German "Manufacturing" sector. The percentage impacts on key aggregate and sectorally disaggregated variables for the German, rest of the EU (REU) and rest of the world (ROW) economies are reported in Tables 2 and 3. The absolute change in sectoral outputs for the same geographical areas are given in Table 4.

It is useful to begin by considering the impact on the German economy, as this is where the direct shock occurs. As expected, there is an increase in GDP (0.1332%) which is reflected in

[10] These proportions are also required for the calculation of the rebound values using equations (2), (A3) and (A4) from Section 3 and Appendix A.

the increase in the returns to capital and labour. However, these effects are small, driven by the limited scope of the efficiency improvement. The increase in the real wage, calculated as the percentage change in the nominal wage minus the percentage change in the CPI, is 0.1387%, whilst the increase in the real payment to capital, calculated in a similar way, is less at 0.0946%. Total consumption rises, broadly in line with GDP and incomes, and both aggregate exports and imports also increase. Energy use in public and private consumption increases at the same rate as total consumption; that is by 0.1453%, which reflects the fixed coefficients assumed in the consumption function.[11] However, the industrial use of energy falls by 1.4965% driven primarily by the fall in energy use in "Manufacturing". As a result, total domestic energy use declines by 0.8069%.

Table 2
Change in key macroeconomic indicators
Scenario 1: 10% increase in energy efficiency in German manufacturing

	Germany	REU	ROW
GDP (Expenditure Approach)	0.1332%	-0.0006%	0.0002%
Exports	0.0254%	-0.0079%	-0.0041%
Imports	0.0322%	-0.0070%	-0.0047%
Public & private consumption	0.1453%	0.0003%	-0.0004%
CPI	0.2309%	0.0034%	0.0000%
Capital rental	0.3255%	0.0088%	-0.0007%
Nominal wage	0.3696%	0.0077%	0.0000%
Aggregate price of energy	0.2440%	0.0078%	0.0001%
Consumption energy use	0.1453%	0.0004%	-0.0004%
Industrial energy use	-1.4965%	-0.0067%	-0.0031%
Total domestic energy use	-0.8069%	-0.0041%	-0.0024%

To get more detail as to the factors underpinning these results, it is useful to turn to Tables 3 and 4 which give sectorally disaggregated information. Again we focus initially on the figures for the German economy. The impact on prices is very clear: "Manufacturing" prices exhibit a small reduction of 0.0833%, reflecting the direct improvement in technical efficiency, whilst the prices in all other sectors rise within the range 0.1741% and 0.3186%, in line with the increases in nominal wages and capital rentals.[12]

[11] This is subject to sensitivity analysis in Appendix Tables B2 and B3.
[12] Recall that the numeraire is the CPI in the rest of the world. The reported price changes are therefore relative to a basket of ROW prices.

The accompanying impact on sectoral outputs is similarly quite clear cut. From Table 4 it is apparent that there is a relatively large increase in output in “Manufacturing” of $6.6314 billion (0.4328%). This is stimulated by a rise in exports, import substitution and increased domestic income as “Manufacturing” goods become relatively cheap. There are also increases in output in other sectors that mainly supply the domestic (public and private) consumption, with an expansion in the “Service” and “Construction” sectors.. However, output falls in the energy sectors (“Electricity and Gas” and “Coke, Refined Petroleum and Nuclear Fuel”) again primarily as a result of the direct improvements in energy efficiency, plus there are falls in other sectors more dependent on foreign trade, such as the “Food, Drink and Tobacco”, “Transport” and “Primary” sectors. In total, output increases by $5.0016 billion.

Table 3
Changes in sectoral price, output and energy use
Scenario 1: 10% increase in energy efficiency in German “Manufacturing”

	Price	Output	Energy
Germany			
Electricity and Gas	0.2732%	-0.9322%	-0.9261%
Coke, Refined Petroleum and Nuclear Fuel	0.1741%	-0.7427%	-0.7105%
Primary	0.2628%	-0.6743%	-0.6907%
Food, Drink and Tobacco	0.2479%	-0.5512%	-0.5910%
Manufacturing	-0.0833%	0.4328%	-4.3559%
Construction	0.2368%	0.1144%	0.0690%
Transport	0.2820%	-0.2761%	-0.1814%
Services	0.3186%	0.0675%	0.0611%
REU			
Electricity and Gas	0.0065%	0.0073%	0.0053%
Coke, Refined Petroleum and Nuclear Fuel	0.0057%	-0.0172%	-0.0247%
Primary	0.0062%	0.0403%	0.0395%
Food, Drink and Tobacco	0.0059%	0.0872%	0.0842%
Manufacturing	-0.0003%	-0.0719%	-0.0780%
Construction	0.0026%	0.0032%	0.0018%
Transport	0.0059%	0.0292%	0.0296%
Services	0.0044%	0.0059%	0.0044%
ROW			
Electricity and Gas	0.0000%	-0.0008%	-0.0010%
Coke, Refined Petroleum and Nuclear Fuel	0.0001%	0.0003%	-0.0002%
Primary	0.0001%	0.0027%	0.0025%
Food, Drink and Tobacco	0.0005%	0.0113%	0.0115%
Manufacturing	-0.0004%	-0.0183%	-0.0194%
Construction	0.0000%	0.0002%	0.0001%
Transport	0.0005%	0.0087%	0.0085%
Services	0.0002%	0.0014%	0.0019%

As we indicate earlier, it is important to understand the impact on Germany, as this is the country that receives the direct economic shock. However, in this paper we are equally, if not more, concerned with the effect on the economies of the rest of the European Union (REU) and the rest of the World (ROW). Of particular interest is the change in energy use outwith Germany's boundaries.

Table 4
Changes in output [Billion 2009 USD]
Scenario 1: 10% increase in energy efficiency in German "Manufacturing"

	Germany	REU	ROW	World
Regional total	5.002	-0.860	-1.973	2.169
Electricity & Gas	-1.579	0.054	-0.016	-1.541
Coke, Refined Petroleum and Nuclear Fuel	-0.526	-0.063	0.005	-0.584
Primary	-0.683	0.315	0.200	-0.168
Food, Drink and Tobacco	-0.940	0.824	0.424	0.308
Manufacturing	6.631	-3.124	-3.422	0.085
Construction	0.337	0.065	0.010	0.412
Transport	-0.424	0.245	0.255	0.076
Services	2.186	0.825	0.571	3.582

It is instructive to begin by considering Table 4. The efficiency improvement in Germany increases world output by $2.169 billion. German output increases by $5.002 billion, but there are reductions in the aggregate value of output in REU and ROW of $0.860 and $1.973 billion respectively. The German sector most strongly affected by the efficiency improvement is the one directly targeted with the shock, "Manufacturing", and the increase in its competitiveness has an important direct impact on the REU and ROW economies. In particular, Table 4 indicates that the $6.631 billion expansion in output in German "Manufacturing" essentially simply displaces "Manufacturing" output in REU and ROW, which fall by $3.124 billion and $3.422 billion respectively. The shift of resources out of "Manufacturing" means that in REU and ROW economies the output in almost all other sectors increases. In both countries the biggest absolute increase in output is in "Services". However, there are also large increases in "Food, Drink and Tobacco", "Transport" and in the "Primary" sectors, which experience a decline in output in Germany. Clearly crowding out in these sectors in Germany leads to expansion in the rest of these external economies.

In Germany there is an increase in both the real wage and the capital rental rate, with the wage increasing more rapidly. With the REU and ROW economies the situation is rather different. In the REU there is an increase in the real return to both factors, but in this case the capital rental rate rises more rapidly. As consumption increases as a whole, REU private and public consumption of energy also increases. However, the rise in the real price of energy, together with the sectoral shifts in the composition of output means that the use of industrial energy falls. In REU, output in the “Electricity and Gas” sector rises but in “Coke, Refined Petroleum and Nuclear Fuel” output falls and total domestic energy use declines.

In the rest of the World (ROW), Table 2 shows that the wage is constant and the capital rental falls. ROW private and public total consumption and consumption of energy decline in line. Again the real price of energy rises and total industrial and domestic energy use fall. In this case the production of “Electricity and Gas” falls but “Coke, Petroleum and Nuclear Fuel” rises.

6.2 Simulation 2: 10% increase in energy efficiency in all German sectors

In this simulation we introduce an across the board 10% improvement in energy efficiency in production in all German sectors. The effects on key aggregate and sectorally disaggregated economic variables are reported in Tables 5, 6 and 7. The first key point from Table 5 is that, as we would expect, the size of the response to the supply-side shock to the German economy is much larger than in Simulation 1. German GDP increases by 0.5159%, the increase in the real returns to labour and capital are 0.5094% and 0.3919% respectively and private and public consumption increases by 0.4948%. However, the proportionate changes in REU and ROW variables are still low, and this is especially important for prices, where the change are small relative to the those that occur in Germany. Recall that the ROW CPI is taken as the numeraire and therefore remains unchanged and the increase in the REU CPI is 0.0034% as against the increase in Germany of 0.2309%.

Table 5
Change in key macroeconomic indicators
Scenario 2: 10% increase in energy efficiency across all German sectors

	Germany	REU	ROW
GDP (Expenditure Approach)	0.5159%	-0.0050%	-0.0024%
Exports	-0.0873%	-0.0168%	-0.0021%
Imports	-0.1503%	-0.0108%	-0.0001%
Public & private consumption	0.4948%	0.0005%	-0.0003%
CPI	0.2079%	0.0048%	0.0000%
Price of capital	0.5998%	-0.0069%	-0.0009%
Price of labour	0.7173%	0.0094%	0.0001%
Price of energy (aggregate)	-1.2698%	-0.0082%	-0.0006%
Consumption energy use	0.4948%	0.0005%	-0.0003%
Industrial energy use	-5.3403%	-0.0600%	-0.0036%
Total domestic energy use	-2.8892%	-0.0386%	-0.0028%

The resulting variation in German commodity prices at a sectoral level primarily reflects the energy intensity of the commodity but, as secondary effects, also the sector’s labour, capital and import intensities. From the figures in Table 6, we observe that the biggest reductions in price occur in the energy sectors themselves, "Electricity and Gas" and "Coke, Refined Petroleum and Nuclear Fuel". This is not primarily because of changes in demand for the output of these sectors but rather because these sectors are themselves very energy intensive in production.[13] The increase in energy efficiency therefore has a particularly marked impact on their prices. Other sectors where prices fall are "Transport", "Primary" and "Food, Drink and Tobacco". Note that in the labour intensive "Services", "Construction" and "Manufacturing" sectors, prices rise.

Table 6
Changes in sectoral price, output and energy use
Scenario 2: 10% increase in energy efficiency across all German sectors

	Price	Output	Energy
Germany			
Electricity and Gas	-1.4237%	-1.9661%	-6.8403%
Coke, Refined Petroleum and Nuclear Fuel	-0.9062%	-0.5980%	-5.0356%
Primary	-0.2409%	0.7805%	-4.7481%
Food, Drink and Tobacco	-0.0937%	0.5278%	-6.5592%
Manufacturing	0.0165%	0.0199%	-4.0749%
Construction	0.2112%	0.4154%	-7.2741%
Transport	-0.3782%	0.6551%	-2.9632%
Services	0.3914%	0.2978%	-5.9916%
REU			
Electricity and Gas	-0.0052%	-0.1858%	-0.1990%
Coke, Refined Petroleum and Nuclear Fuel	-0.0040%	-0.3649%	-0.3819%
Primary	0.0018%	-0.0860%	-0.0768%
Food, Drink and Tobacco	0.0024%	-0.0142%	-0.0106%
Manufacturing	0.0048%	0.0278%	0.0516%
Construction	0.0060%	0.0017%	0.0075%
Transport	0.0056%	-0.0506%	-0.0369%
Services	0.0063%	0.0097%	0.0200%
ROW			
Electricity and Gas	-0.0007%	-0.0350%	-0.0335%
Coke, Refined Petroleum and Nuclear Fuel	-0.0005%	-0.0381%	-0.0366%
Primary	-0.0004%	-0.0215%	-0.0199%
Food, Drink and Tobacco	-0.0004%	-0.0026%	-0.0015%
Manufacturing	0.0001%	0.0122%	0.0167%
Construction	0.0001%	0.0001%	0.0011%
Transport	-0.0004%	-0.0159%	-0.0152%
Services	-0.0001%	0.0029%	0.0050%

Output falls in the two energy sectors but increases in all others. The proportionate figures reported in Table 6 are slightly misleading: from Table 7 we observe that the sector that has the

[13] Changes in demand for a commodity only affect its price in this long-run model in so far as they change the economy wide factor prices. As a result of the general equilibrium adjustments after a shock, it is quite possible for the demand for a commodity to rise, with no change in its technology, but and for its price to fall.

second smallest (0.2978%) proportionate increase in output, “Services”, has the largest ($9.647 billion) absolute increase. The 0.4948% rise in domestic consumption demand is driving this change in “Service” output and the increase in the output in this sector requires resources to be shifted from other sectors. We know that the energy sectors will release resources and the relatively small increase in output in “Manufacturing” implies that resources will be released here too. In this simulation, overall both German exports and imports fall, so that the increase in activity involves import substitution. Domestic private and public consumption of energy increases by 0.4948% but this is completely dominated by the 5.3403% fall in industrial energy use, so that total domestic energy use declines by 2.8892%.

Table 7
Changes in output [Billion 2009 USD]
Scenario 2: 10% increase in energy efficiency across all German sectors

	Germany	REU	ROW	World
Regional total	10.117	-1.311	-0.065	8.741
Electricity & Gas	-3.331	-1.364	-0.713	-5.408
Coke, Refined Petroleum and Nuclear Fuel	-0.423	-1.326	-0.648	-2.397
Primary	0.791	-0.672	-1.587	1.468
Food, Drink and Tobacco	0.900	-0.134	-0.099	0.667
Manufacturing	0.305	1.210	2.286	3.801
Construction	1.222	0.035	0.006	1.263
Transport	1.006	-0.424	-0.469	0.113
Services	9.647	1.364	1.158	12.169

The sectoral responses from both the REU and ROW economies are, in this case, qualitatively similar. Total output summed across all sectors falls in both regions: by $1.311 billion in the REU and by $0.065 billion in ROW. There are reductions in output in the two energy sectors, reflecting both the lower industrial demand in Germany plus the increased competitiveness of the German energy sectors. These output reductions in the REU and ROW energy sectors are less, in absolute terms, than the corresponding declines in Germany. However, they make up almost 40% of the world reduction in the energy output resulting from the improvement in German energy efficiency. Also these energy sectors are the sectors generally showing the largest absolute reductions in output in REU and ROW. Only the “Primary” sector in the ROW registers a bigger fall.

In the “Services”, “Construction” and “Manufacturing” sectors, REU and ROW output increases in line with the expansions in the German economy. In Germany these are sectors that benefited from the German expansion in consumption, but have become less competitive against production in REU and ROW. On the other hand, the “Food, Drink and Tobacco” and

"Primary" sectors show reductions in REU and ROW outputs which are moving contrary to the changes in German output. These are REU and ROW sectors which are now less competitive than their German counterparts.

The proportionate impact on aggregate variables in REU and ROW is shown in Table 5. Both aggregate exports and imports are reduced for REU and ROW. There is a small rise (0.0005%) in public and private consumption in REU but a small proportionate fall of 0.0003% in ROW. In both regions, the real wage rises and the real return on capital falls. This change in the relative factor prices is particularly marked in REU. Clearly capital released from the energy sectors is difficult to reabsorb in the expanding sectors driven by increased German consumption demand. In REU, private and public consumption of energy increases but this is dominated by the reduction in production, so that total domestic energy use falls by -0.0386%. In ROW, energy use in both private and public consumption and in industry falls, with total ROW domestic energy use declining by -0.0028%.

7. Rebound calculations

7.1 Scenario 1: a 10% increase in energy efficiency in German "Manufacturing"

The figures in column 3 of Table 3 give the sectorally disaggregated proportionate changes in energy use that result from the 10% increase in energy efficiency in the German "Manufacturing" sector. The first point to note is that the actual reduction in energy use in German "Manufacturing" is 4.3559%. Using equation (1), this translates to an own-sector rebound value, R_i, of 56.44%. However, recall that this is not limited to direct rebound in that it incorporates all the general equilibrium effects that impact on this sector. This value, and all the other rebound values, are given in Table 8.

Table 8
General equilibrium rebound effects for Scenarios 1 (10% increase in energy efficiency in German "Manufacturing") and Scenario 2 (10% increase in energy efficiency across all German sectors)

	Own-sector R_i	Own-country production R_p	Own-country total R_d	Global EUR$_g$	Global WorldR$_g$
Scenario1					
Rebound [%]	56.44	47.63	51.31	50.22	48.11
Change [% points]		-8.81	3.68	-1.09	-2.11
Scenario 2					
Rebound [%]	n.a	46.60	50.18	47.28	46.58
Change [% points]			3.58	-2.90	-0.70

The primary interest of this paper is to investigate how rebound values change as the scope of the measure is extended from own sector energy use to incorporate energy use in other sectors, other (consumption) uses and other economies. It is sometimes implied that such increases in scope will necessarily increase the rebound value. Our results show that this is not the case.

The first extension is to include the use of energy in production in the other German sectors, so as to calculate the own-country production rebound value, R_p. Equation (4) shows that the measured rebound will rise, so that $R_p > R_i$, if there is an increase in the energy used in the production of other, non-“Manufacturing”, sectors as a result of the increase in energy efficiency in the “Manufacturing” sector. Table 2 shows a reduction in total German industrial energy use of 1.4965%. We use equation (2) to calculate the rebound value, R_p, taking the value of α, the share of “Manufacturing” in total energy use in German production, from Table 1. This produces a rebound value of 47.63%. This reduction in rebound occurs primarily because of the fall the output in the energy sectors, which are themselves energy intensive. The price of energy falls relative to the components of value added but increases in price relative to other commodities, so that the change in the energy intensity of production within individual sectors will be small.

A similar procedure, outlined in Appendix A, is used to calculate the total domestic rebound value, R_d, in the target economy (Germany). This measure incorporates energy used in domestic private and public consumption. In this case, private and public consumption increases, generating a rise in energy use in consumption by an equal proportionate amount. This leads to a rise in the rebound value to 51.31%.

However, we are most concerned with the change in the measured rebound values when changes in energy use in the REU and ROW are taken into account. From the results reported in Table 2, it is clear that the total domestic energy use in both REU and ROW falls as a result of the energy efficiency gain in German “Manufacturing”. In both regions, total output declines and there is a large reduction in “Manufacturing” output. The result is that the rebound incorporating all changes in energy use in the EU, EUR_g, takes a value, 50.22%, that is slightly less than the German whole-economy domestic rebound. Similarly the world rebound value, $WorldR_g$, is lower still at 48.11%.

7.2 Scenario 2: a 10% increase in energy efficiency in all German sectors

The rebound values for Scenario 2, where the energy efficiency improvement applies across all German sectors, are very similar to the values for Scenario 1. For each of the rebound calculations, the Scenario 2 value is slightly less than that for Scenario 1 but the qualitative relationship between the different rebound measures is retained. There is a substantial rebound of 46.60% in energy use in total German production. When the whole economy rebound is calculated, the value is increased by 3.58 percentage points as a result of the increase in energy use in public and private consumption. However, as was observed in the rebound associated with the Scenario 1 simulations, the extension to include REU and ROW energy use reduces the measured rebound. The combined effect in this case is a slightly larger reduction of 3.60 percentage points with the biggest reduction occurring in the REU segment.

8. Conclusions and directions for future research

In the case of policies that aim to increase energy efficiency, a major concern has been the existence of countervailing rebound effects that generate increases in energy demand that partially (or possibly wholly) offset expected energy savings. These effects operate through the reduction in the price of energy in efficiency units, which thereby generate substitution and income effects which operate to at least partly offset the reduction in energy use generated by the direct efficiency gain. This paper extends the analyses of ‘economy-wide’ rebound from the national focus of previous studies to an international one. In particular it investigates whether international spillover effects from trade in goods and services have the potential to change the overall (global) rebound of local energy efficiency improvements. On that account, we propose a measure of economy-wide rebound that is appropriate for use if the accounting boundaries are expanded beyond the borders of the national economy where the efficiency improvement takes place. Whether rebound rises or falls as the boundaries are extended depends on whether there is a net increase or decrease in energy use in the area of activity being introduced.

Our model suggests that at the global scale rebound effects are significant. 10% energy efficiency improvements in German “Manufacturing” and in German production overall are associated with global rebound values of 48.11% and 46.58%. That is to say, almost a half of any expected energy saving through improved energy efficiency in production will be taken by rebound effects. However, the results do not show that restricting the focus of the rebound calculation to the economy in which the improvement occurs underestimates the rebound effect: quite the reverse. The rebound values fall in both of the simulation scenarios performed here where the energy use outwith Germany is incorporated in the rebound calculation.

The logic is straightforward. The standard energy leakage argument concerns policies where firms are encouraged to reduce energy consumption by making energy relatively expensive (through a carbon-tax, regulation or cap and trade policy). However, the rebound phenomenon occurs around policies which encourage the adoption of energy saving technologies where, in the treated activities, energy efficiency improves. Especially where the policy extends across all production sectors, the relative competitiveness of energy intensive commodities in the target country increases. This means that in other countries their production will, in general, become less profitable, and therefore be discouraged. This is reflected in the results obtained in this paper. In the simulations we report, the value of the domestic rebound actually overestimates the global rebound. Of course, we use a general equilibrium system, so that other forces are simultaneously at work. Further, the size and detail of the rebound effects will differ in specific cases.

For pedagogic reasons, the model we use here imposes a number of limiting assumptions. Key amongst these are: that that there is no substitution across commodities in consumption; that supplies of capital and labour are fixed in each country; and that all factors of production are always fully employed.

Sensitivity analysis, reported in Tables B2 and B3 in Appendix B suggest that increasing the elasticity of substitution between commodities in consumption will increase domestic and global rebound values. However, the qualitative character of the results remains. The rebound values measures that incorporate changes in energy use outwith Germany have lower values and the size of the difference remains relatively stable. In future developments, relaxing the supply-side assumptions will be the main priority. First, a key area will be the introduction of a more flexible and sophisticated treatment of capital and labour markets. This would involve consideration of investment, labour supply and migration. Moreover, modelling capital stock and labour market adjustments across regions would introduce dynamic adjustment of factor supply which would allow investigation of the evolution of global rebound over time.

Second, given its importance in our results, a priority must be to develop a more sophisticated treatment of energy supply. This should include (but not be limited to) consideration of the manner in which capacity decision are actually made (which adds emphasis to the need to effectively model dynamic adjustment in general), the impact of increasing exploitation of renewable energy sources and technologies, and how energy prices are determined in local and international markets.

Finally, applications of the type of modelling framework presented in this paper (and further augmented in ways already discussed) would be invaluable in considering the domestic and international spill-over effects of domestic policies designed to increase efficiency in household energy use, and the implications in terms of interdependence between energy efficiency policy implementation (for example, under EU 20-20-20) in one nation and energy use in others.

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APPENDIX A

To consider the full economy-wide rebound effect in the domestic economy, *d*, we must also consider the impact on energy used in meeting the (final) consumption demands of the economy, which generally equates to household energy consumption. Thus, the own-country economy-wide rebound formulation, R_d is given as:

$$R_d = \left[1 + \frac{\dot{E}_d}{\beta\gamma}\right] 100. \tag{A1}$$

where β is the initial (base/reference year) share of sector *i* energy use in total energy use (in both production and consumption) in the domestic economy, *d*. The term $\dot{E}_d / \beta\gamma$ can be expressed as:

$$\frac{\dot{E}_d}{\beta\gamma} = \frac{\Delta E_d}{\gamma E_i} = \frac{\Delta E_i + \Delta E_p^{-i} + \Delta E_c}{\gamma E_i} = \frac{\dot{E}_i}{\gamma} + \frac{\Delta E_p^{-i}}{\gamma E_i} + \frac{\Delta E_c}{\gamma E_i}, \tag{A2}$$

where the *c* subscript indicates 'consumption' (households). Substituting equation (A2) into equation (A1) and using equations (1) and (4) gives:

$$R_d = R_p + \left[\frac{\Delta E_c}{\gamma E_i}\right] 100. \tag{A3}$$

which is equation (5) in the text.

The global rebound rebound effect, R_g, defining the impact on world energy use resulting from increased efficiency in the use of energy in sector *i* within the home economy, *d*:

$$R_g = \left[1 + \frac{\dot{E}_g}{\chi\gamma}\right] 100, \tag{A4}$$

where χ is the initial (base/reference year) share of sector *i* (within country *d*) energy use in world energy use (in both production and consumption).

The term $\dot{E}_g / \chi\gamma$ can be expressed as:

$$\frac{\dot{E}_g}{\chi\gamma} = \frac{\Delta E_g}{\gamma E_i} = \frac{\Delta E_i + \Delta E_p^{-i} + \Delta E_c + \Delta E_g^{-d}}{\gamma E_i} = \frac{\dot{E}_i}{\gamma} + \frac{\Delta E_p^{-i}}{\gamma E_i} + \frac{\Delta E_c}{\gamma E_i} + \frac{\Delta E_g^{-d}}{\gamma E_i}, \quad \text{(A5)}$$

where the *-d* subscript indicates global energy use outwith the domestic economy receiving the efficiency shock. Substituting equation (A4) into equation (A5) and using equations (1), (4) and (A3) gives:

$$R_g = R_d + \left[\frac{\Delta E_g^{-d}}{\gamma E_i}\right] 100. \quad \text{(A6)}$$

which is equation (6) in the text.

APPENDIX B

Table B.1
List of sectors

Sector	Associated WIOD Sectors / NACE Classification
Electricity and Gas	40
Coke, Refined Petroleum and Nuclear Fuel	23
Primary Goods	1t2, 5, 10t14, 20
Food, Drink and Tobacco	15t16
Manufacturing	17t18, 19, 21t22, 24, 25, 26, 27t28, 29, 30t33, 34t35, 36t37
Construction	45
Transport	60, 61, 62
Services	50, 51, 52, 55, 63, 64, J, 70, 71t74, 75, 80, 85, 90t93, 95

In Tables B2 and B3 we report rebound values for three different specifications of the public and private consumption function. These comprise; the default (Leontief), a Constant Elasticity of Substitution (CES) and a Cobb-Douglas functional forms. The different specifications exhibit different elasticities of substitution between commodities in consumption. The values are 0, 0.5 and 1 respectively. As expected, the rebound values rises as the elasticity increases because there is substitution towards the commodity whose price has fallen, which is relatively energy intensive in production. However, the relative ordering of the rebound effects does not change.

Table B.2*
Sensitivity analysis with regard to consumption structure
Scenario 1: 10% increase in energy efficiency in German "Manufacturing", but assuming different elasticities of substitution for consumption (es_c)

	Own-sector R_i	Own-country production R_p	Own-country total R_d	Global EU R_g	Global World R_g
Leontief composite					
Rebound [%]	56.44	47.63	51.31	50.22	48.11
Change [% points]		-8.81	3.68	-1.09	-2.11
es_c = 0.5					
Rebound [%]	57.05	48.29	52.22	50.96	48.86
Change [% points]		-8.76	3.93	-1.26	-2.10
Cobb-Douglas composite					
Rebound [%]	57.63	48.93	53.12	51.68	49.63
Change [% points]		-8.70	4.19	-1.44	-2.05

Change of household energy use	**Germany**	**REU**	**ROW**
Leontief composite	0.1453%	0.0004%	-0.0004%
es_c = 0.5	0.1551%	-0.0017%	-0.0008%
Cobb-Douglas composite	0.1653%	-0.0038%	-0.0013%

Table B.3*
Sensitivity analysis with regard to consumption structure
Scenario 2: 10% increase in energy efficiency in all German sectors, but assuming different elasticities of substitution for consumption (es_c)

	Own-country production R_p	Own-country total R_d	Global EU R_g	Global World R_g
Leontief composite				
Rebound [%]	46.60	50.18	47.28	46.58
Change [% points]		3.58	-2.90	-0.70
es_c = 0.5				
Rebound [%]	47.57	55.87	53.50	53.03
Change [% points]		8.30	-2.37	-0.47
Cobb-Douglas composite				
Rebound [%]	48.55	61.58	59.74	59.50
Change [% points]		13.03	-1.84	-0.24

Change of household energy use	**Germany**	**REU**	**ROW**
Leontief composite	0.4948%	0.0005%	-0.0003%
es_c = 0.5	1.1454%	0.0141%	0.0027%
Cobb-Douglas composite	1.7991%	0.0274%	0.0057%

APPENDIX C

To model actual policies that aim to improve energy efficiency, the commitment of resources to basic research or R&D needs to be incorporated together with some form of financing. This would be similar to a full simulation analysis of policies to raise the productivity of labour through increased Higher and Further Education spending (Hermannsson et al. 2014): initial investment leads to subsequent efficiency improvement. A key element would need to be the effectiveness with which the commitment of resources to research translated to improvements in energy efficiency. This would be an econometric issue not central to the analysis here and not important for rebound.

In so far as the investment in knowledge capital requires resources, the financing impact on competitiveness and/or consumption demand could be important. In the present model, public and private expenditure is combined. Therefore the prior commitment of resources to research would simply mean a change in the allocation of expenditure between sectors in the period before the efficiency improvement is introduced, which could have positive or negative effects on energy use. In general, the public or private funding of the research would have more complex economic implications, again raising different sorts of issues.

Independently of the financing of the basic R+D, if the implementation of efficiency improvements by firms requires additional costs in the form of an increased use of resources, this complicates their character as efficiency improvements. Essentially it will reduce the competitiveness effects of the efficiency improvements. However, the introduction of a technique which reduces energy use but does not reduce the firm's unit costs (at existing intermediate input and factor prices) is not an efficiency improvement. This is simply a change in technique which substitutes increases in other inputs to offset a reduction in energy inputs. It is a change which firms would have to be induced to make. An efficiency improvement requires the production of more output with less input. It is this characteristic which makes it such an attractive option.

If again we were to attempt to model the actual introduction of a policy which had such costs, the extent of the true efficiency change would be a key issue, together with the extent that other inputs were effectively substituting for energy, together with the relative scarcity (the economic cost) of such inputs. These would be important determinants of the actual impacts of the policy and its cost effectiveness. We do not attempt such a specific and holistic analysis here. Rather, we focus solely on one important aspect of such a policy. This is the extent of rebound and how that varies as the geographical scope of the analysis changes.

About the Authors:

Simon Koesler is based at ZEW (Centre for European Economic Research), Mannheim, Germany.

Kim Swales is Emeritus Professor, Department of Economics, University of Strathclyde.

Karen Turner is the Director of the Centre for Energy Policy, University of Strathclyde International Public Policy Institute.

Contact details:

Simon Koesler
ZEW
Mannheim
Germany
e: koesler@zew.de

Kim Swales
Department of Economics
University of Strathclyde Business School
e: j.k.swales@strath.ac.uk

Karen Turner
Centre for Energy Policy
International Public Policy Institute
University of Strathclyde
e: karen.turner@strath.ac.uk
t: +44 (0) 141 548 3198

International Public Policy Institute (IPPI)
McCance Building, Room 4.26
University of Strathclyde
16 Richmond Street
Glasgow G1 1XQ

e: ippi-info@strath.ac.uk
t: +44 (0) 141 548 3865

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University of Strathclyde Glasgow

the place of useful learning
www.strath.ac.uk/ippi
ippi-info@strath.ac.uk
University of Strathclyde Glasgow G1 1XQ